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REALIZING THE EDUCATIONAL PROMISE OF TECHNOLOGY

Secondary Students Break Into Genetics Research

Students crack the DNA code for mice and dragons.

BY CHAD DORSEY AND RANDY VON SMITH

Two student interns are bent intently over computer monitors. In a nearby building, tens of thousands of mice scurry in cages, each labeled with their specific genetic strain. Years of painstaking laboratory breeding have developed each strain's unique characteristics. Some mice always become obese. Some are bald. Others have extra large ears. One kind even glows bright green under ultraviolet light. These famous mice are the reason students are here, studying genetics. Suddenly, one student gasps in surprise. Pointing to the image on her companion's screen, she exclaims, "How did you get yours to breathe fire?"

A similar scene marked the early stages of the *GENIQUEST* project, a collaboration between the Concord Consortium and the Jackson Laboratory in Bar Harbor, Maine. Of course, the organisms on the computer screen weren't a new strain of fire-breathing mice. Instead, they were the dragons that so many students have come to know through our BioLogica genetics software. The project brings cutting-edge genetics research techniques to high school students.

GENIQUEST stands for Genomics Inquiry through Quantitative Trait Loci Exploration with SAIL Technology. The

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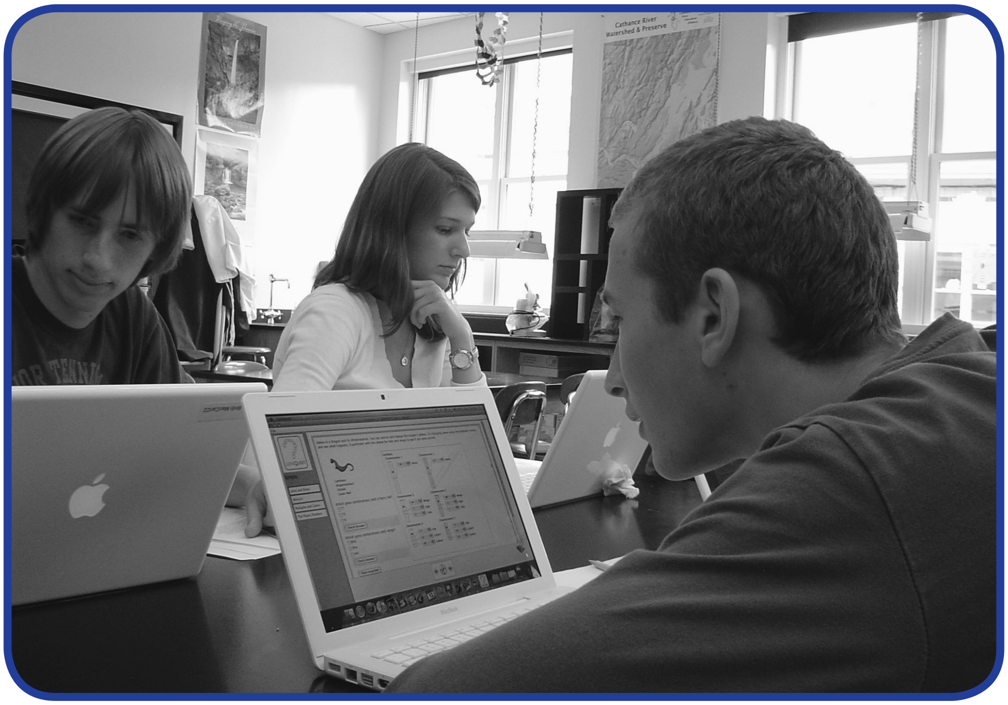

Inside

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Preparing Student Scientists for Tomorrow

BY CHAD DORSEY

It's an exciting time for science. Knowledge in long-standing fields such as biology is increasing at exponential rates. Significant new discoveries are being unearthed. At the same time, traditional science disciplines are merging into entirely new and still evolving entities. Nanoscience. Bioinformatics. Molecular electronics. Chemical biology. This terminology describes ideas and combinations so diverse that it is often difficult for outsiders to imagine what they encompass. It can be equally difficult for scientists in these fields to keep tabs on the changes from month to month. Surveying this shifting landscape makes it almost possible to imagine how thrilling it must have felt to be involved in science in the time of the Enlightenment when theories and worldviews from the early days of chemistry and astronomy toppled under the challenge of new evidence and modes of thought.

> We prepare students for a world that is changing **even as they learn about it,** and ready them for careers that are **as yet unnamed.**

It's an equally exciting time for science education. We prepare students for a world that is changing even as they learn about it, and ready them for careers that are as yet unnamed. Headlines of the latest discoveries seem lifted straight from science fiction novels—discoveries of light-bending, "invisible" materials, teleporting atoms, personalized medicine, or genetic engineering cause us to wonder how science teaching should even begin to address them.

But what is really new about these new sciences? And are things actually changing as quickly as it seems? Certainly in some cases, the answer is a definitive "Yes." In biology, for example, the amount of publicly available DNA sequence data has doubled every 14 months for 20 years. Samples from a single round-the-world voyage of the recent Global Ocean Survey quadrupled the number of proteins known to exist in the world. A technique announced in January promises to make DNA sequencing 30,000 times faster, completing an entire human genome in less than 30 minutes for under $1,000. The biological information explosion will not slow anytime soon.

This burst of information has brought fundamental changes in our knowledge of biology and in the way science is conducted. Scientists have witnessed the radical transformation of their tools and techniques in response to the torrents of data their experiments now produce. Data have become king, and harnessing and analyzing them have become the reigning challenge. As described in the article "Secondary Students Break Into Genetics Research," entire new fields of computational biology, bioinformatics, and metagenomics have arisen seemingly overnight.

In other areas of science, the changes are different, but equally significant. As our ability to examine and manipulate the world reaches new scales, other changes come not from the immensity of the data, but from the minuteness of its size. In the miniscule realm of nanoscale science, individual atoms are the fundamental scale. The standard Newtonian physics that has served us so well now gives way as the spooky effects of quantum mechanics dominate. Understanding this poses a new challenge—in designing a nanoscale circuit or assembling structures from individual atoms, we must understand not only how atoms and molecules behave, but also how electrons interact with each other and their surroundings.

LINKS *Student Scientists*

- **GENIQUEST** *http://geniquest.concord.org*
- **Electron Technologies** *http://et.concord.org*
- **Molecular Workbench** *http://mw.concord.org*
- **Science of Atoms and Molecules** *http://sam.concord.org*

As these and other sciences evolve, the Concord Consortium is keeping pace. We are developing projects that anticipate the skills and knowledge students will need to meet the challenges of these new sciences. The GENIQUEST project fills the need for bioinformatics understanding by bringing cutting-edge genetics research to high school students. Our *Electron Technologies* project extends our groundbreaking *Molecular Workbench* software from atomic and molecular dynamics to pioneer scientifically rigorous, interactive simulations of the bizarre quantum behavior of electrons. (See sidebar for one student's view of working with Molecular Workbench. MW helps Britiany and countless students like her prepare for the future.)

These and our many other projects demonstrate some of the numerous attributes that will be required of instruction and curricula in order to meet the challenges of the changing science landscape.

Complex topics demand deep understanding.

To grapple with the incredible complexity of new sciences, students need robust, highly interactive computational models such as those in our Molecular Workbench or BioLogica software. Interacting with our models helps students better understand tough concepts and retain them longer than with other materials.

Interdisciplinary fields require unifying concepts.

As students move into a world that blurs the lines between traditional fields such as chemistry, physics, and biology, understanding crosscutting principles becomes essential. Our *Science of Atoms and Molecules* (SAM) project responds to this need. This project, highlighted in this issue's Monday's Lesson, brings the notion of an inverted sequence science curriculum—with physics first, chemistry central, and biology as capstone—to its logical extension: If we're going to teach these topics in a different order, we must also *teach them differently*. By making the study of atoms and molecules central to all subjects, the SAM activities provide a unifying thread across the curriculum. Such a fundamental understanding will help students succeed in the new interdisciplinary sciences.

New curricula must fill in the wide gaps that current curricula leave.

The rise of new sciences introduces complex new ideas and topics into both science study and everyday life. To live in a world of personal DNA results and genome-wide association studies, students will need clear knowledge of topics such as bioinformatics. Current textbooks often devote only a page or two (of a whopping 1,000 or more) to the topic. To understand the critical dynamics of the nanoscale world, students and technicians need a deep understanding of the quantum effects of electrons. Current curricula in this area offer mostly page-long equations and inscrutable jargon.

Guided inquiry curricula from our projects address this gap directly. By targeting the knowledge students need, we can skip past many often tired topics that are included by tradition, but offer only suspect usefulness. This does not mean that we discard fundamentals—indeed, they're as important as ever. But the curricula for this new era must use these fundamentals to build understanding of carefully chosen overarching concepts. Current curricula are overstuffed with vocabulary or mired in the inch-deep-mile-wide process of national adoption. Our curriculum and software address the core of current student knowledge needs and bring solid pedagogy along in the process.

As we continue in this era of scientific change, we need tools for learning that do the change justice. Having these tools at our disposal makes facing the future truly exciting. By using the new approaches that our software and curricula offer, we can bring students the coherent scientific understanding they need to become informed future scientists and citizens.

Chad Dorsey *(cdorsey@concord.org) is President of the Concord Consortium.*

One Student's View of Molecular Workbench

By Britiany Sheard, student
Bowling Green State University

My experience with Molecular Workbench has been amazing. Using Molecular Workbench in my Physical Chemistry class, I was able to understand the dynamics of properties, systems, and processes visually. For instance, I was able to run experiments by setting up simulations and changing one property at a time. I think all Physics and Chemistry classes should use Molecular Workbench because it provides an alternative way to grasp concepts outside of just lecturing in the classroom. It allowed me to explore in a way unimaginable before when I built a fuel cell simulation step by step myself. I could let my curiosity flow by exploring how each editing tool affected my creation. I could also see other simulations built by students from around the world. Thus, I was able to learn in two ways—by attempting my own experiment and by analyzing other simulations.

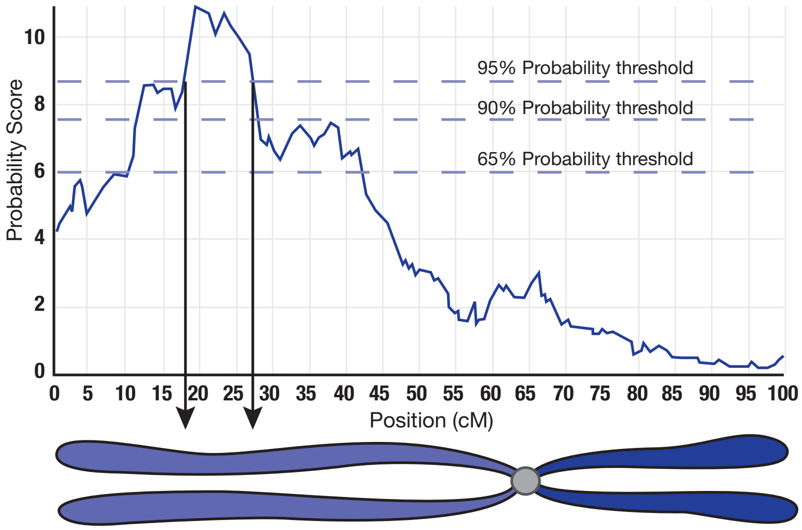

Figure 1. An example of a plot used in Quantitative Trait Loci (QTL) analysis. This graph shows the probability that a certain area on a chromosome (displayed below the graph) contains genes related to the trait being studied. The arrows point to the region of the chromosome that is 95% likely to contain the desired genes.

Genetics research on computers

When you think of a "genetics researcher," you might imagine a scientist in a lab coat working with chemicals, tubes, and other laboratory apparatus. Although this picture is still accurate in many places, a new and very different one is emerging. Databases and computer-based analysis techniques have changed the face of much of biology research, especially genetics.

Like their more traditional counterparts, researchers in this new field—dubbed bioinformatics—make stunning breakthroughs across a broad range of genetics fields. However, they often make their discoveries with the aid of a computer rather than a pipette.

New DNA analysis techniques in the past decade have fueled an exponential increase in the amount of available biological information. This explosion has turned databases such as the Jackson Laboratory's Mouse Genome Database into critical research tools and has paved the way for statistical methods such as Quantitative Trait Loci (QTL) analysis. With QTL, computer science, math, and biology merge.

project builds on Jackson Laboratory's 75-year history of student summer interns and the lab's recent success extending this outreach to magnet high schools such as the Maine School of Science and Mathematics and the North Carolina School of Science and Mathematics. Jackson Lab researchers mentor students in the latest genetics research techniques, including Quantitative Trait Loci (QTL) analysis, a statistical process used to pinpoint the location of unknown genes.

Breeding dragons

Students are transported to a mythical island where dragons live. They begin by breeding and studying the dragons to confirm the basic Mendelian genetics they have learned in the classroom. Mysteries crop up, however, when students discover a trait whose cause they can't identify through the software. Some dragons develop plates on their upper neck, but the gene that controls this trait is not obvious.

To learn more, students "attend" a research conference on the island and read research papers from famous dragon scientists. They investigate the appearance of these mysterious plates by breeding individuals. Then they examine the offspring's chromosomes, using their knowledge of the parent strains and information about the recombined DNA in

What is QTL analysis?

Genetics, history, and environment shape who we are. Specific traits like height, skin color, a tendency to obesity, or the development of diseases like diabetes can be a manifestation of genetic traits. The majority of these are "complex traits," representing the interaction of many genes. Science and medical researchers are interested in determining what regions of the genome are linked to specific traits, especially traits for human diseases or conditions, for example, high cholesterol levels.

One technique begins with organisms about which we already know much. Strains of mice are carefully bred so that every mouse of a certain strain is genetically identical. Specific locations on the genome are used to identify each strain.

If we have one strain of mice that always has high cholesterol levels and another that always has low cholesterol levels, we can breed them and study the offspring. Because genetic crossover during breeding mixes the genes of the two strains, the offspring have mixed genomes. After breeding many offspring in a controlled way, the genomes of the resulting offspring represent a diverse mix of the two strains jumbled across all the specially identified locations on the genome.

The next step is to study the offspring and their cholesterol levels and examine their "jumbled genomes" at each of the previously identified locations. If any of these locations are consistently associated with the original strain that *always* had high cholesterol and occur in individuals that have high cholesterol, it is very likely that genes in those locations have some control over the cholesterol levels. We use a statistical process known as Quantitative Trait Loci (QTL) analysis on the large population to make that association and, thus, to identify probable regions of the genome for further investigation.

the offspring to narrow down the possible location of the gene for neck plates. By simple manipulation of a powerful model, students experience the power of statistical techniques and learn why scientists require large numbers of individuals to zone in on a possible genomic location.

Later, when a disease breaks out on the island, students must put their knowledge about QTL analysis to work. The survival of dragons depends upon them! Students work to identify an area on a chromosome as the probable location of the disease gene and then hunt down the specific gene in a genetics database.

Computational genetics

In addition to teaching genetics concepts through a powerful model, GENIQUEST also introduces students to important tools and processes of computational genetics research. Researchers study mice as a "model organism" for humans because mice and humans are genetically 98% similar. Studying mice allows researchers to explore many models for human disease in cases where direct experimentation on humans is not possible. Likewise, "on the island," experimentation on dragons is not permitted (in this fictional world, it takes 500 years for dragons to breed), so students must conduct research on another fictional animal, the drake.

To ensure that the underlying genome for both dragons and drakes was an accurate scientific analog, Jackson Lab researchers extended the original BioLogica genome by slicing the actual mouse genome into 50 parts, rearranging them randomly, and reassembling them with many genes removed. The resulting genome bears the same relationship to the mouse genome that our human genome does. Because it also has the same level of complexity as the mouse and human genomes—though with many fewer genes—computational biology techniques such as QTL analysis yield valid results in sizes that are manageable for students to explore.

With this enhanced BioLogica software, students learn the basics of QTL analysis and gain practice using the mouse database genome browser to research information about specific genes. When students pinpoint the probable disease location on a chromosome, they search for their answer within the actual Jackson Lab mouse gene database used by researchers worldwide.

SAIL

SAIL (Scalable Architecture for Interactive Learning) is both a framework and a collection of applications and databases that permit non-programmers to create, modify, and deploy from the Web dynamically created learning activities with embedded highly interactive simulation, modeling, probeware, graphing, and analysis components. All the work a learner does while interacting with a SAIL client-based activity–visiting pages, answering questions, creating a drawing, investigating a model, collecting data from probes–is saved over the network and is available for the learner when the activity is run again. In addition, the learner's work is available for a teacher or researcher to review.

The current SAIL framework, which is an outgrowth of the NSF-funded Web-based Inquiry Science Environment, has been developed by the NSF Center for Technology Enhanced Learning in Science (TELS) to support the development of inquiry learning investigations. SAIL represents over a decade of prior research into technology-enhanced student learning.

Further study

LINKS *Genetics Research*

GENIQUEST
http://geniquest.concord.org

With this background, students are prepared to embark on further study of real genetic data and scenarios. For instance, students might start with a QTL dataset that has already been published and test themselves, seeing if their analysis of the dataset leads them to the same genes that researchers identified as candidate genes for that dataset. Or they could analyze data from QTL analyses from numerous studies that have been publicly shared, but only partly analyzed.

Especially eager or advanced students could even run their own analysis on any of the huge number of public datasets that have not yet been tackled. This would offer the possibility of uncovering original research results, and require no more equipment than their standard computer. Magnet school students working with Jackson Lab regularly explore these possibilities, and advanced AP Biology students with a background from the GENIQUEST project would be well equipped to use it as well. With an understanding of biology concepts rooted in investigation of a robust biological model, students can approach biological problems on much firmer ground. Today's GENIQUEST students might lead the way in tomorrow's genetic research, unlocking mysteries important not only to dragons, but to humans as well.

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Teaching Evolution with Models

BY PAUL HORWITZ

In 2005 only a quarter of the U.S. adult population subscribed to the idea that modern-day organisms evolved through "natural causes."* Some people, to be sure, believe in a literal interpretation of the Bible, but for many more it is simply not conceivable that the extraordinary complexity and interdependence we observe in living things could be anything other than the result of intentional design. To most of us it is quite literally incredible that random change, accompanied by variance in reproductive fitness ascribable to inherited traits, can produce the same outcome without intentionality and with no external intervention.

The fact that our model evolves **doesn't prove evolution** by natural selection, it simply **illustrates it.** And that, with support from the National Science Foundation, is what we have set out to do.

Yet a simple computer model can demonstrate how evolution occurs. Imagine a simplified model of a plant that needs only one thing—water. If just enough water is present the plant will grow and produce seeds, which will germinate and eventually produce other plants, which in turn will make their own seeds and offspring. If there is a bit too much or too little water, the plant will be sickly and produce fewer seeds or no seeds at all. In extreme cases—if the plant gets much too much or far too little water—it will die without producing any offspring at all.

While this model is easy to build on a computer, it has one major flaw—it is unstable. If the birth rate exceeds the death rate on average, the number of plants will grow without limit; if the inequality is reversed, they will die off. Luckily, the problem is easy to fix. We need to ensure that fewer plants grow to maturity when they are "overcrowded"—which is, of course, what happens in nature.

Where's the evolution?

So far, so good, but where does evolution come in? Imagine that our model plants come in different varieties. Some are adapted to more water, some to less. For simplicity, let's assume that there are 10 varieties of plant. Level 1 is adapted to live in very dry climates, and level 10 in very wet ones. Note that the two extreme varieties are likely to look quite different. For instance, a level 1 might have a very long taproot like a dandelion, while a level 10 might have shallow roots that spread out laterally. But nearby varieties don't differ much at all. A level 4 plant looks almost the same as a level 5.

Now we know that offspring don't always look

* "Public Divided on Origins of Life," Pew Forum on Religion and Public Life (2005).

Four types of model plants: note the differences in leaves and roots. Plants with small leaves are adapted to high light conditions, bushy plants thrive in less light. Deep roots are adapted to dry climates, shallow ones to wet.

LINKS *Teaching Evolution*

Evolution Readiness
http://er.concord.org

exactly like their parents; even the littermates of purebred dogs show some variation. How do we add this important feature of the real world into our model? Easy! Imagine that when a plant produces seeds *the offspring sometimes shift levels*. So a level 5 plant, for instance, will mostly produce level 5 offspring, but every once in a while it will make a level 4 or a level 6 plant. Assuming that the original plant was in a level 5 environment—that is, that it was getting just the right amount of water—its level 4 and level 6 offspring will be slightly disadvantaged. They will probably die young and have fewer seeds on average, and, therefore, fewer offspring. And if they have offspring that are still more maladapted to the environment—level 3 or level 7, say—those will never go to seed and will produce no offspring at all. So the population of plants will stay more or less at level 5, with the occasional 4 or 6, which may well go unnoticed since they look so much like the level 5's. Still no evolution? Wait, we're getting there. Just one little thing to add to the model…

Environmental pressure

Environments are not eternal. Weather patterns change. Some rivers dry up, others flood their banks. Ponds fill in and become marshes and wetlands and eventually dry land. What will happen in our model if we vary the environment? Try this mental exercise. To that computer model in your head add a slider with a range from 1 to 10, corresponding to different amounts of water, each suitable to the different levels of plant. At the outset the slider is set to 5 and the model starts out with a hardy population of level 5 plants "growing" on your mental screen, with the occasional 4 and 6 mixed in, as described above. What will happen if you move the slider to 10, causing the environment to become a lot wetter? Think about that before reading further.

The answer is that it depends on how fast you move the slider. If you move it too fast, the entire population of plants will die off. But if you move it slowly enough the plant population will have time to adapt and will eventually evolve from level 5 to level 10. Relying only on the fact that the plants aren't all the same at each generation, and that those that are more adapted to the environment are likely to have more offspring, the population of plants will—over many generations—adapt even to enormous changes in the environment. And it does this entirely through natural processes!

Of course, in a way we cheated, didn't we? We created all those different levels of plants, specifically designed to thrive in all those different environments, before we even ran the model. It evolved, all right, but it evolved into something that was there to begin with! Point well taken. The fact that our model evolves doesn't *prove* evolution by natural selection, it simply *illustrates* it. And that, with support from the National Science Foundation, is what we have set out to do.

Evolution Readiness

In a recent project called Evolution Readiness, we are building the model described above, among others. Starting in the fall, we plan to try it with fourth grade students at schools in Massachusetts, Missouri, and Texas. For example, we will challenge the students to make a plant population evolve by gradually altering its environment, and we will monitor their actions to see what they do. Since the roots of the plants are not visible "in the wild," the student must move a plant into a virtual laboratory in order to see its roots. If we observe students doing this spontaneously, we can reliably infer that they are looking for differences between the plants and associating those differences to changes in the environment.

> We will **challenge the students** to make a plant population evolve by **gradually altering its environment,** and we will monitor their actions to see what they do.

This spring our collaborators at Boston College will present fourth graders at each participating school with an assessment designed to measure their understanding of evolution and some associated "big ideas," such as natural selection. Next year and in 2011, we will compare this baseline data to the performance of students taught by the same teachers, who have used our models and curricular materials. This summer we will host a three-day workshop for a dozen teachers plus administrators and technical supervisors from the three participating schools. We will keep in touch with the teachers through an online course.

The Evolution Readiness project is a challenging one. Although the individual concepts we cover—adaptation, variability, and inheritance—are included in state and national science standards for the elementary grades, they are rarely integrated and presented as a mechanism for evolution. We will be working very closely with participating teachers over the next two years to achieve that goal.

Paul Horwitz *(phorwitz@concord.org) is Co-Principal Investigator of the Evolution Readiness project.*

Teaching About Molecules w

BY DANIEL DAMELIN

Try it out

Go to: http://mw.concord.org

Launch Molecular Workbench and click "Trust" to run the application. Go to the Activity Center, and then click the link to Cellular Respiration.

Note: You will need Java installed to run this activity.

Thousands of different chemical reactions are taking place in your body as you read this sentence. Ions and molecules are colliding, diffusing, and reacting at a frenetic pace. In other words, molecules and their interactions are the very stuff of biology and scientists are learning more about these biomolecular reactions every day. Their research fuels the biotechnology industry and guides the search for a cure for cancer and many other diseases. Because of its importance in modern research and industry, biochemistry is now taught in biology courses, including high school biology.

Teaching chemistry in biology

As content leans more toward the molecular level and an understanding of biochemical processes, biology teachers are challenged to teach chemistry to students who frequently do not have a significant grounding in chemistry. Additionally, the types of molecules biology teachers refer to are often large and complex.

To make these molecules more understandable, teachers use different kinds of representations: Fischer projections, abbreviated names for large molecules like NADH, and cartoon views for really large molecules like proteins.

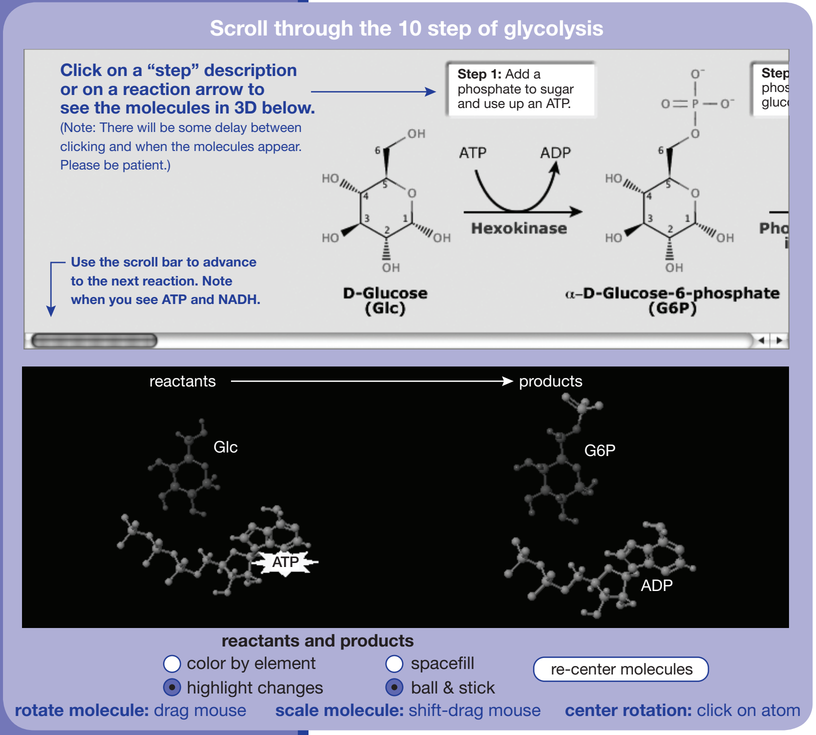
Most students enter biology only having experienced simple formulas and ball and stick views of basic molecules. When faced with unfamiliar molecular representations, students may feel as if their previous knowledge about molecules doesn't apply in biology class. One way to help students understand the chemistry happening in their biology class is to present molecules in various representations at the same time. In our "Cellular Respiration" activity, developed by the *Science of Atoms and Molecules* project, we do just that.

Glycolysis and the Krebs cycle

The Cellular Respiration activity begins by teaching about glycolysis and the Krebs cycle. Typically this is taught using only the molecular representations shown at the top of the figure at left.

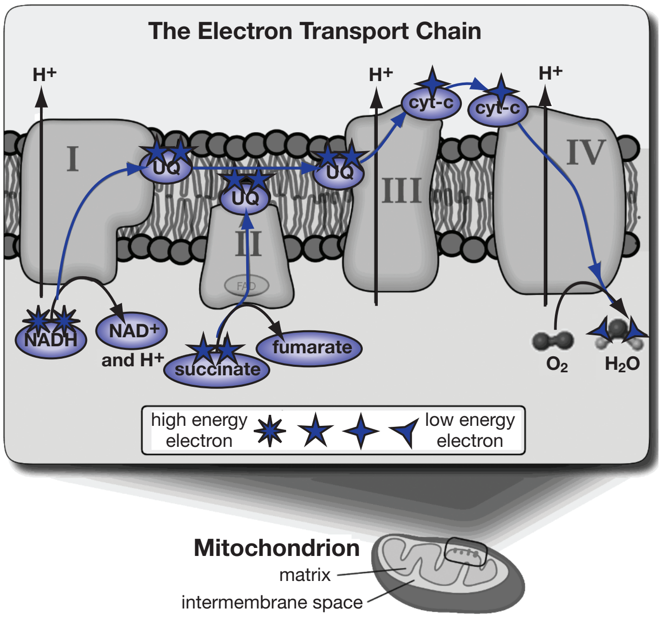
Students can click on any of the reaction arrows to see the molecules represented in the more familiar ball and stick form. The interactive 3D molecules also give students different ways to view the molecules, for example, by coloring them to highlight what has happened in the reaction. Students can then follow how the atoms are rearranged to form new molecules.

The goal is not for students to memorize every step of glycolysis or the Krebs cycle, but to provide tools to help students make connections between different representations of molecular structures (e.g., 3D, ball and stick, and formulas) and to help them see patterns in how atoms are exchanged during reactions by giving them control over various ways of looking at the molecules.



Multiple representations allow students to make connections between symbolic forms of chemical reactions and the more familiar ball and stick representations. The 3D ball and stick views are interactive and can be colored to highlight the changes that occurred during the chemical reaction.

vith Multiple Representations



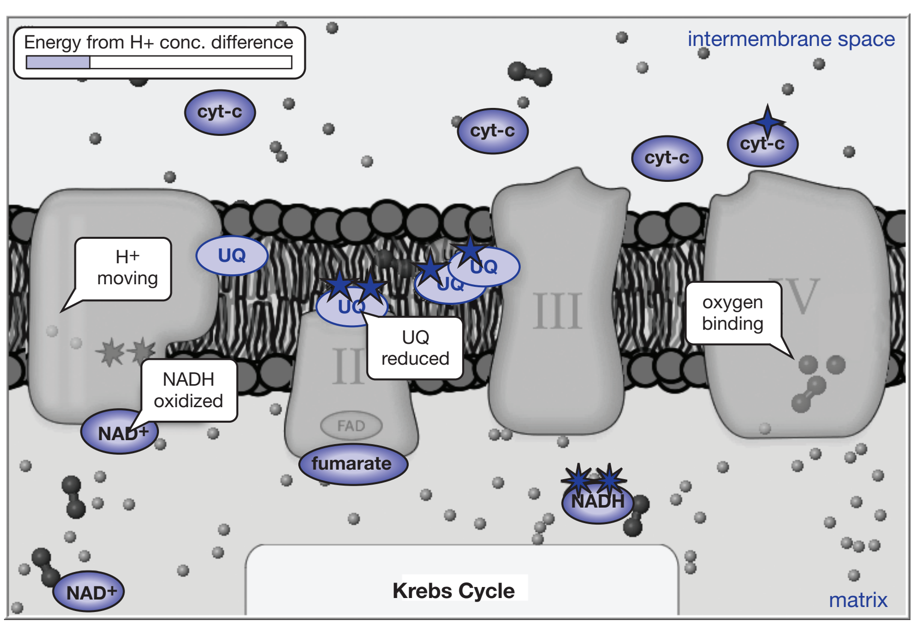
Biochemistry and the misrepresentation of dynamic processes

The atomic world is frenetic and random. Molecules vibrate, move, collide, and react at a phenomenal pace. They don't know where they are or where they are going, yet biochemical pathways are commonly diagrammed as if things happen in an ordered sequence and in a directed manner.

The electron transport chain involves many protein complexes and cofactors, some of which are anchored to the inner mitochondrial membrane, and some of which move, floating in random directions, buffeted by water and other molecules surrounding them. But that dynamic unchoreographed action is not evident in the typical illustrated diagram (see figure above). Here it appears as if NADH and succinate "know" just what to do and that the path of the electrons follows a smooth unbroken sequence from beginning to end. While these diagrams are very helpful in understanding the overall outcome, they oversimplify the true nature of the dynamic world of atoms and molecules.

In the latter parts of the Cellular Respiration activity the models depict a more realistic view of what is happening in the electron transport chain (see figure below). The chemical energy (represented as high energy electrons) produced in molecules generated by glycolysis and the Krebs cycle is used to push hydrogen ions from one side of the inner mitochondrial membrane to the other. Eventually the energy stored in the high hydrogen ion concentration is used to make ATP, a crucial molecule that powers many chemical processes in your body.

Viewing a dynamic model of such a complex system can be overwhelming at first, but it can provide insights that static pictures just can't convey. To begin, focus your attention on one protein complex at a time and study it until you get a sense of its function isolated from the rest of the electron transport chain. (The model facilitates this: when you click on one of the protein complexes, only that complex will be visible.)



LINKS *Monday's Lesson*

RI-ITEST *http://ri-itest.concord.org*

Science of Atoms and Molecules
http://sam.concord.org

Expanding our view of the biomolecular world

By helping students to make connections through multiple representations—from a molecular formula to a complex illustration to a dynamic model—we give them tools to better understand the world around them. Experts easily translate from one representation to another and know which one is best for the type of critical thinking they need to do at that moment. Our goal is to help students learn to think more like experts, to facilitate their increased understanding of the molecular world, and to provide them with the tools experts use as well as the facility to know when to use them.

Daniel Damelin *(ddamelin@concord.org) directs the Rhode Island Information Technology Experiences for Students and Teachers (RI-ITEST) project.*

Digital Resources Poised to Reshape Science Learning

BY CAROLYN STAUDT AND ANDY ZUCKER

Driving questions

Why are there clouds?
What do plants eat?
What if there was no friction?
What is electricity?

Two important education trends are beginning to converge and the Concord Consortium's Universal Design in Science Education is at the intersection. Our project is one of the first integrated science education programs to embody Universal Design for Learning (UDL) principles. Electronic curricula and UDL principles are both of growing importance to schools, where computers are more common than ever and the student population is increasingly diverse.

What are UDL principles? They're like the curb ramps that help wheelchairs and baby strollers get from the sidewalk to the street. Designed for accessibility for certain subsets of the population, items based on UDL principles help all people. In science software, UDL features—such as text-to-speech, glossaries, coaches, scaffolding, Smart Graphs* and Smart Models—offer educational mobility to all kinds of students, including those with disabilities and English language learners. The challenge, and our goal, is to design these features well so they are fully integrated and transparent to students.

Science units

Our instructional materials offer students and teachers multiple representations and means of expression, and a variety of assessment strategies. Four science units were developed around driving questions for grades 3-4 and 5-6. Each unit includes four rich model-based, probe-based, and hands-on science activities.

A fictional story and a math activity accompany each science unit to engage students and introduce the driving question. This addition of science-related stories can encourage teachers to integrate reading and science instruction, an important factor for adoption of curricula in districts where reading dominates the time allocated for instruction of all kinds. The stories provide an additional cognitive channel for students to learn the science information. Since standardized testing also focuses on math skills, we included a related math activity to integrate concepts.

A "wrapping up" activity provides students with a portfolio of their own artifacts—including text responses to embedded questions, drawings, snapshots, and models in a saved state—that they can use to demonstrate what they have learned. Pre-test and post-test questions provide a parallel, more traditional assessment.

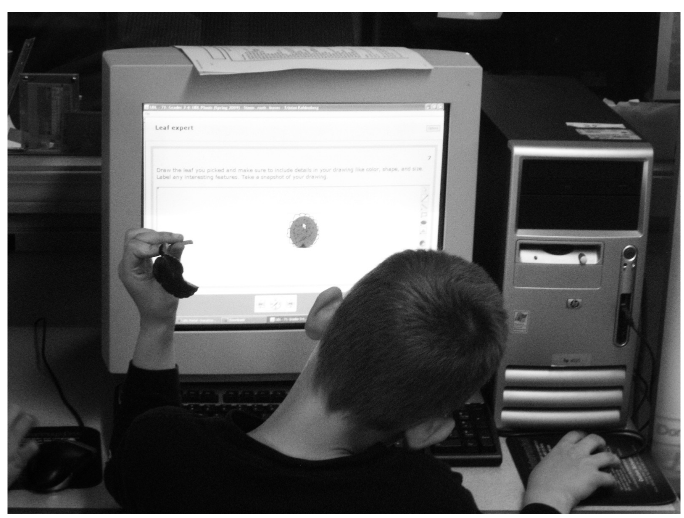
Lessons learned

Reports available from the initial research in two large urban districts provide intriguing glimpses into student understanding of our selected driving questions. Based on the actions and answers of 316 students to questions in the Intermediate (grades 5-6) Clouds unit we learned several lessons.

1. Sequencing

Students learn science through experimentation and guided inquiry. Often, this occurs in ways that teachers or researchers can't predict. Students approach learning with their existing understanding, building on prior ideas that may not agree with scientists' ideas of the world. We designed the units to provide a variety of inquiry investigations in a flexible manner. To support individual students working at their own pace on different activities, we dictated no particular sequence among the six activities available in each unit. Teachers could select subsets of these activities based on their time limitations.

Reviewing the student reports indicates that sequencing needs to be more deliberate; students should encounter new terms and concepts in a more methodical way (for instance, by insisting that the story is read at the beginning), and



Computer-based activities engage students. In this example, a student is using an online drawing tool to draw a leaf as part of the "What do plants eat?" unit.

* See "Monday's Lesson: What's So Smart About a Graph?" in the Winter 2009 *@Concord*.

must have practice applying new terms before constructing descriptions of complex phenomena. Identifying the order within the complete set of activities as well as providing a shortened sequence of key activities for teachers with limited time will ensure both flexibility and well-supported student learning.

2. Language learning

The specialized vocabulary used in science is a barrier for many students, especially those who are still learning English or who have learning disabilities. We help lower this barrier by including features that make text more accessible to students. First, students can change font size to make the text larger or smaller to suit their preferences and visual abilities. Second, when students highlight text on the screen (by dragging a mouse over the text), the software reads the text aloud. Additionally, words shown on the screen in blue are defined in a glossary. When students click on one of these words they are first prompted to provide a definition of their own. The software then displays the definition supplied by the curriculum authors. Students can also click on a glossary icon that displays the entire set of glossary words for that unit.

Nearly 70% of students in these trials clicked on one or more glossary words. The median number of words for which students sought definitions was three (though some 46 students used the glossary 50 or more times!). Every student also used the text-to-speech feature at least once. To build on this success, we are expanding and refining the glossary words and definitions.

3. Scaffolded prompts to embedded questions

An additional UDL feature we incorporated into these units was scaffolded question prompts. Students encountering questions within the unit receive varying levels of context and assistance to aid them in their answer. These supports can range from a quick reminder to use pertinent information from the unit to a sample exemplary response. Teachers may assign a specific level of scaffolding to students. Students may also select different levels of scaffolding support to help them with individual questions. This scaffolding helps students both to answer the question correctly and to put that correct response in the context of the overall learning goals around the driving question for the unit.

Because student responses to all questions embedded in the software units—including their drawings, graphs produced using probes, and answers to constructed and multiple-choice items—are stored on a server, we can view detailed information about how students interact with this and other features. We learned that nearly one-third of the students looked at or responded to scaffolding at a higher level than the one they were assigned by the teacher. Additionally, a few students (3%) clicked through the various levels of scaffolding before answering the original question. Examining the reports further, we also discovered that many questions were related to the immediate tasks rather than to the important underlying concepts. Students could answer the immediate questions, but could not make the leap to the next conceptual level. As we revise these questions, we plan to add scaffolding to more questions to assist students in making these important connections.

LINKS *Digital Resources*

Universal Design in Science Education
http://udl.portal.concord.org

CAST
http://www.cast.org

4. Coaches

The Center for Applied Special Technology (CAST) has done significant work studying brain networks. They have identified three primary networks (affective, strategic, and recognition) and their function in learning. CAST has applied this information to reading comprehension. In our UDL units, science coaches—animated robots that address the student with prompts, hints, and models—are aligned with each network and help students by sparking ideas and questions around the science content. The affective coach seeks to engage and motivate students by linking scientific knowledge and exploration to students' real-world experiences and goals. The strategic coach helps students focus on what they need to know and how they can go about finding that out. The recognition coach guides students in gathering facts through exploration, observation, and experimentation and helps them both to display and interpret their results.

Despite the coaches' potential value for motivation and explanation, very few students used the coaches. To address this, we plan to introduce coaches in a more meaningful and deliberate manner. We will automatically activate the coaches when novel technology tools for graphs, models, or probes are used; when new language or key concepts are introduced; or as a prompt to help students review ideas before moving to activities with more sophisticated concepts. This will help us learn more about how coaches may help students increase their science understanding.

Next steps

Our initial research demonstrates that many students use the available UDL features. These students report that the features are helpful. As more and more school districts adopt 1:1 computing, such features will become essential components in digital science curricula. Our research will help identify the most promising of these features—the "curb ramp" elements aiding science instruction. We will continue to analyze student data for the remainder of the school year. Our findings will serve to improve the science curriculum materials for the final year of testing (2009-2010). By revising and improving features based on our data and continued student and teacher feedback, the curriculum will support all elementary science students with high-quality instruction.

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Constructive Chemistry: A Case Study of Gas Laws

BY CHARLES XIE AND AMY PALLANT

Science should be taught as a verb as well as a noun. Performing science is a compelling and effective way to learn. It is through the process of exploration, creation, and invention that theories are applied, ideas are tested, and knowledge is synthesized and advanced.

Teaching by engaging students in creating their own artifacts can be traced to Seymour Papert's advocacy of *Logo* through its offspring *AgentSheets*, *StarLogo*, *NetLogo*, *Scratch*, *Squeak*, and others. By creating animations and games with these tools, students are enticed to learn core mathematical and programming concepts and apply them to their creations. In physics, *Interactive Physics* and the recently released *Phun* and *Crayon Physics*, with which students can easily create physics-based simulations that model the real world, have shown great potential in teaching Newtonian mechanics.

Our Molecular Workbench (MW) software can be used in a similar way. Unlike the tools mentioned above, MW is specialized to model electrons, atoms, and molecules, which makes it applicable across physics, chemistry, biology, and engineering. Interactive simulations produced with MW allow students to learn through exploration and inquiry. Students can also learn by creating their own simulations that show emergent behaviors under various conditions. As students create simulations, they learn important concepts in science, how those concepts are connected, and how to apply them to design working systems.

Because the *Molecular Workbench* simulation engine calculates the motion of atoms and molecules based on their interactions, it can model a considerable depth and breadth of science. With this versatility and a graphical user interface for creating simulations, MW is perfectly suited for educators interested in exploring the constructionist approach of teaching science with computer simulation tools.

Over the last two years, we have collaborated with chemistry professor Neocles Leontis at Bowling Green State University (a science teacher preparation institution in Ohio) to pilot test the constructionist strategy in his physical chemistry course. The results may provide lessons for the wider adoption of this pedagogy.

Digging more deeply into the gas laws

Professor Leontis challenged his students to answer questions by designing molecular simulations. One of the challenges concerns the Ideal Gas Law: $PV=Nk_BT$, where P is the pressure, V is the volume, N is the number of molecules, k_B is the Boltzmann constant, and T is the absolute temperature. Professor Leontis posed a number of questions that he would not have been able to ask his students before, because without high-level analytical skills involving advanced mathematics or computation, the questions can't be easily answered. But because *Molecular Workbench* is a tool for solving complex problems with just a few mouse clicks, he did not have to worry about his students' mathematical backgrounds. He was confident that they could answer his questions using MW simulations.

LINKS *Constructive Chemistry*

Molecular Workbench
http://mw.concord.org

Why must *N* be the number of molecules?

The first challenge asked students to think about why N has to be the number of molecules instead of the number of atoms. To answer this question, a student compared two containers that had the same number of atoms, but in one container she created a covalent bond between every two atoms (Figure 1). Thus, she produced a gas of diatomic molecules and reduced the number of freely moving entities to half.

Running the simulation for a while, she observed that the volume of the gas in the right container decreased to about half the volume of the gas in the left container. A careful observation of the simulation immediately revealed why. As the two atoms of a molecule move together, when one of them bounces off the piston, the other has a high probability of being towed away without hitting the piston. As a result, the frequency with which atoms collide with the piston decreases by half.

Does the mass of the molecules affect the gas law?

Figure 2 shows a student's simulation designed to investigate this ques-

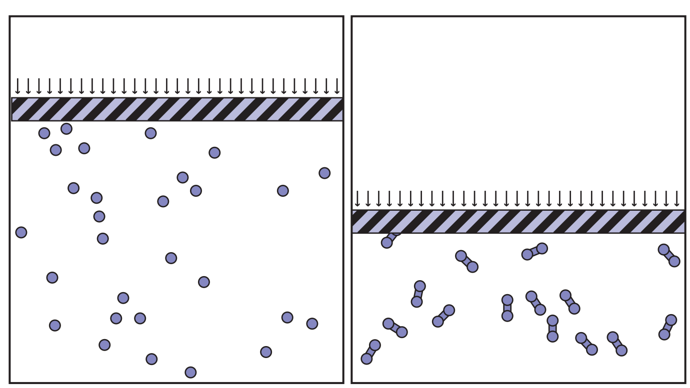

Figure 1. A simulation created by a student showing that the volume of a gas of 15 diatomic molecules is only half that of a gas of 30 atoms. The atoms in both containers have exactly the same properties, and the pressure, temperature, and pistons are identical.

tion. The gas in the left container (A) is composed of atoms that are three times more massive than the atoms of the gas in the right container (B). The simulation shows that under the same external pressure and temperature, the volumes of both gases turn out to be about the same after they reach equilibrium. This means that the average volume an atom occupies depends only on the pressure and the temperature, even though the atoms in A appear to move at an average speed that is only half that of the atoms in B. This is quite a surprising result!

How do atoms of different masses "know" to keep their distance? The answer can be found by observing the collisions of the atoms with the pistons. Each collision of an atom with the piston in A delivers an average impulse that is twice as much as each collision of an atom with the piston in B. In order for the gases to have the same pressure, the frequency of the atom-piston collisions in A must be half of that in B. Considering that the atoms in A move half as fast, the only way to keep the frequency of the atom-piston collisions in A half that in B is to keep the density of atoms—hence the volume—the same.

Can you break the Ideal Gas Law?

Students are often motivated by the challenge to design something that violates a physics law. They are inspired to use their creativity. One student designed a subtle experiment in which all the atoms in one container moved perpendicular to the piston while the atoms in another container moved in all directions with an initial setup that guaranteed the equipartition of kinetic energy in each direction (Figure 3).

After running his simulation, he wrote, "I found out that the volume of the particles that are moving in 1D is larger than the volume of the particles moving in 2D even though they all have the same speed. I assume, however, since momentum is conserved, that the net speeds in both simulations are the same, but the difference is that in the 1D model, all the momentum is in the y-direction. Let's call all of this momentum P. In the 2D model, half of the momentum is conserved in the x-direction ($P/2$) while the other half is conserved in the y-direction ($P/2$), which leads me to believe that the 2D model's piston should have half the height as the 1D model's piston." Indeed, the simulation shows that the volume of the gas in the right container is approximately half that of the gas in the left container. Is the Ideal Gas Law broken? We leave the answer to you.

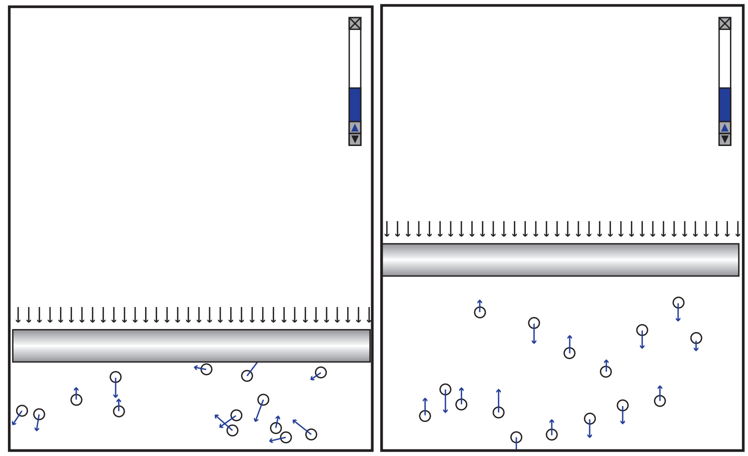

Figure 3. A simulation created by a student showing that if all particles move only perpendicular to the piston, the volume of the gas will be twice as much as if they are moving in all directions, if the external pressure, temperature, and number of particles are identical.

Concluding thoughts

Although this pilot test was done with college students, there is nothing to prevent high school teachers from trying this constructionist pedagogy. A unique strength of *Molecular Workbench* is that it permits teachers to scaffold a challenge activity to help students design their own simulations. For example, Professor Leontis put two identical models side by side on a page and asked students to modify one so that it would exhibit a different behavior of scientific significance. This scaffolding design ensures that students will not be intimated by the complexity of the software and lowers barriers for student engagement.

The simulations created by Bowling Green students indicate that students can learn important ideas when they use their imagination and create their own simulations to solve challenges. Indeed, some of their simulations reveal solutions that even we had not considered. As Albert Einstein said, "Imagination is more important than knowledge. For knowledge is limited to all we now know and understand, while imagination embraces the entire world, and all there ever will be to know and understand." These students have proven Einstein's assertion and we are grateful for their insights about gas laws and how we should teach them.

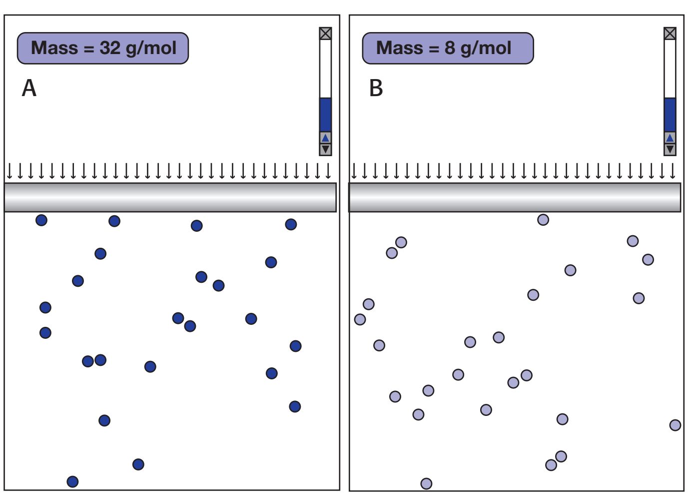

Figure 2. A simulation created by a student showing that the volumes of two gases, one consisting of atoms that are three times more massive than those of the other, are approximately the same, if the pressure, temperature, and number of atoms are the same.

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Du Châtelet Rediscovered

BY ROBERT TINKER

I was delighted recently to discover two books and a play about a brilliant Enlightenment scientist whose importance has only recently been realized: Emilie Du Châtelet. She lived in France and produced her most important work between 1735 and 1749. She was a polymath, probably one of the brightest thinkers of her time. She made many original contributions to understanding heat and light, but she has been ignored and unknown until recently.

She created a **comprehensive and coherent synthesis of ideas** about religion, philosophy, and the science of astronomy, heat, and motion that had been circulating.

Du Châtelet's greatest contributions to science were two monumental works: *Institutions de physique* (Foundations of Physics) and *Commentaire* on Newton's *Principia*. In *Institutions*, she created a comprehensive and coherent synthesis of ideas about religion, philosophy, and the science of astronomy, heat, and motion that had been circulating. This was an ambitious undertaking that was more complete than anything Newton had attempted. Selecting ideas from Newton, Leibniz, Descartes, and many lesser known "natural philosophers" of the period, she created her own synthesis. *Institutions* was well received and earned her wide recognition as a leading philosopher.

Science of the Enlightenment was all mixed up with religion and politics. Truth was dictated by one's homeland. You were either in the English Protestant Newton camp, or the French Catholic Descartes camp, or the German metaphysical Leibniz camp. Emilie Du Châtelet managed to transcend these divisions and combined the best ideas regardless of nationality and religion.

Du Châtelet's *Commentaire* was also a bold effort that started as translating Newton's *Principia*, but became an authoritative exposition of mechanics that was far more easily understood than the original and contained three important experimental verifications of Newton's results that had been completed in the half-century since its publication. She also corrected errors, such as Newton's assumption that the earth was homogeneous. But most importantly, she used the modern Leibniz calculus notation instead of Newton's idiosyncratic and difficult fluxions. Because of nationalistic politics, English scientists rejected this improved approach, and her formulation put French physics ahead of England's for two hundred years.

There was persistent confusion about heat at the time—whether it had mass, how it was stored and liberated, where it went, and how light and flame related to heat. The dominant theory stated that a substance called phlogiston was liberated by fire and flowed into other materials. It wasn't until the 1780s that Lavoisier disproved phlogiston by burning materials in sealed containers. But the idea died hard.

Reviews

Passionate Minds: Emilie Du Châtelet, Voltaire, and the Great Love Affair of the Enlightenment by David Bodanis (Three River Press) 2006.

Emilie Du Châtelet: Darling Genius of the Enlightenment by Judith Zinsser (Penguin) 2006.

Legacy of Light, a play by Karen Zacarias, commissioned by and premiered on the Arena Stage in Crystal City, VA, May 8, 2009.

Molecular Workbench and Enlightenment Science

The Enlightenment scientists did not know about atoms and their interactions and were, therefore, unable to understand heat. The following Molecular Workbench simulations could have saved them all considerable confusion.

1. Du Châtelet and Voltaire were struggling with what heat was. It would have all snapped into place if they could have seen our article "What flows when heat flows?" *http://www.concord.org/publications/newsletter/2006-fall/mondays-lesson.html*
2. Du Châtelet wanted to know how much heat was in light. The molecular models at *http://workbench.concord.org/database/activities/283.html* help explain this and demonstrate how different colors of light heat matter.
3. Du Châtelet was right to focus on mv^2, which turns out to be twice the kinetic energy of an object. If she had the following activity, she could have seen how energy and Newton's Laws could explain heat. *http://workbench.concord.org/database/activities/308.html*

Mulling over these issues, in 1737 Du Châtelet had the temerity to hold that light was massless, an extraordinary, original, and correct idea. She realized that light traveled extremely fast and reasoned that if it had mass, its impact on earth would be devastating. She also measured the heating caused by different colors of light and discovered that there was invisible light that could warm a thermometer, what we call infrared light.

Du Châtelet's most celebrated original contribution was to identify energy with mv^2 and to posit that energy was conserved, that one form of energy might be converted to another, but that the total energy was constant. This was a major break with Newton who focused on mv, a scalar quantity that he observed could disappear in a collision.

Her science alone should have earned her widespread recognition, but her unconventional love life overshadowed her science. Her brilliance made it inevitable that she and the second-best thinker of the time, Voltaire, became lovers for over a decade. He supported and inspired her, but also undercut her. When they first discovered each other, they collaborated on a translation of Newton that he published under his name, though her contributions appear to have overshadowed his.

Voltaire fancied himself an original scientist and entered a competition held by the French Academy on the nature of heat. He undertook extravagant but uncontrolled experiments to measure the mass of heat. She helped during the day and then wrote her own entry for the competition at night and secretly submitted it. They both won commendations, but hers would have won if she had been established and male.

Her science alone should have earned her widespread recognition, but **her unconventional love life** overshadowed her science.

Du Châtelet died at 42, her life cut short by a fatal pregnancy. Because she was a woman who died young, and because Voltaire and French society belittled her posthumously, her contributions have been almost invisible. The current explosion of interest in her has led to two important books and a brilliant play. Both books cover the many fascinating twists and turns of Emilie Du Châtelet's life. *Passionate Minds* is shorter and quite absorbing, so I recommend it as a way to enter her world. The Zinsser book is more authoritative and provides far more detail.

"Legacy of Light" intertwines Du Châtelet's story with that of a fictitious modern astrophysicist who is also a woman. The resulting tapestry is good theater, witty and memorable. The play moves deftly over time and space, combining riveting sketches with absorbing lectures about the culture and science.

Both scientists deal with the dual demands of science and the biological reality of conceiving and bearing children. Without preaching or moralizing, the play addresses these age-old issues head on, balancing the tragedy of Emilie Du Châtelet's life with a more successful resolution in the present. The play also treats the science accurately and thoughtfully. Students interested in science would find it an accessible way to learn the process and some key ideas of science, and every young woman would find new role models in the play.

These publications mark the resurrection of Du Châtelet and her science. They begin to fill in a missing link in the history of science. She helped clarify the fuzzy thinking of the time at considerable personal cost. It is unfortunate that she cannot shine even today on the strength of her brilliance without being illuminated by the brighter flame of Voltaire, even though his science was far inferior.

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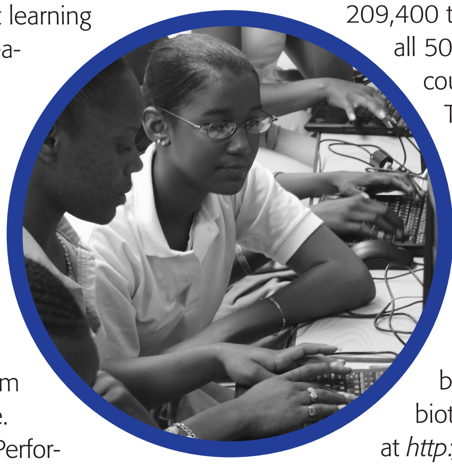
NEWS at Concord Consortium

Electronic Circuits and Online Performance Assessments

In previous work we have found that students' scores on question-and-answer tests are not reliable predictors of their ability to perform a corresponding task. This finding casts considerable doubt on the central premise that the assessment tools we use to evaluate student learning constitute a reliable measure of the knowledge and skills we intend to measure. Insofar as the entire United States educational enterprise increasingly revolves around just such assessments, a methodology for dramatically improving them could be transformative.

The Simulations for Performance Assessments that Report on Knowledge and Skills (SPARKS) project will produce a sequence of computer-based assessments using simulations of electronic circuits and test equipment. Aligned to the content of an introductory college-level electronics course, these assessments will be designed for the classroom or as self-paced tests to be taken by students outside of class. As students build simulated circuits and test them, their actions will be monitored and analyzed for evidence of content knowledge and troubleshooting skills. Results will be reported to the students, who will be given the opportunity to correct errors and improve their performance.

The three-year project is funded by a grant from the Advanced Technological Education (ATE) Program of the National Science Foundation, and is a collaboration of the Concord Consortium, CORD, and Tidewater Community College.



Over 200,000 Molecular Workbench downloads

In the last two years, our Molecular Workbench software has been downloaded 209,400 times from users in all 50 states plus over 150 countries worldwide. That's an average of 500 students using these activities daily.

Download the free software and learn about the molecular world with activities for physics, chemistry, biology, nanoscience, biotechnology, and more at *http://mw.concord.org.*

Global Lab Goes To Russia

In the 1990s, students from 120 high school classes worldwide participated in the first NSF-funded Global Laboratory Projects by exploring outdoor study sites and indoor air quality and sharing their local histories with an online community. Begun at TERC in Cambridge, Massachusetts, under Boris Berenfeld and Robert Tinker, Global Lab has a new incarnation at the Concord Consortium and the National Training Foundation of the Russian Federation.

With funding from the World Bank to the Russian Ministry of Education, Global Lab has been transformed into a two-year integrated science curriculum for students in grades 5-6. Used by more than 30 schools in the broad Russian Federation as a core science course, the curriculum aims to teach not only science process skills, emphasized by the first Global Lab, but also all science concepts prescribed by the comprehensive Russian National Standards. In addition to a student textbook, teacher guide, and lab and field journals—all freely available online as PDF documents—teachers can download 100 multimedia lessons on environmental science.

The Russian National Training Foundation offers teacher preparation master classes run by project staff and experienced teacher-trainers. Russian Global Lab *(http://www.globallab.ru)* hopes to recruit 50 to 60 additional Russian schools this year and welcomes international participants.

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